Lecture Outline

- Reading from reader
- Sign up for poster session (Dec. 11 or 12) today or e-mail me

- Today’s Lecture
  - Assembly of Hinged MEMS Structures
  - Assembly of MEMS With Other Microdevices
    - Serial Assembly (pick & place)
    - Parallel Assembly Processes
      - Guided Transfer
      - Self-Assembly
Assembly and MEMS

• “This new technology, originating in microelectronics, offers the possibility of fabricating **fully assembled**, low-cost mechanical devices and systems …” (emphasis added)
  
  • *Small Machines, Large Opportunities*. NSF Workshop on MEMS Research, 1987-1988 (K. Gabriel, J. Jarvis, and W. Trimmer, eds.)

Assembling Hinged Structures

• Enable assembly of 3-D structures from surface micromachined parts
  
  • Manual assembly, fluidic agitation
  • On-chip MEMS actuators
  • Parallel external methods
On-chip Actuation Methods

- Use actuators (i.e., comb drives, vibromotors, scratch drives) to push hinges into assembled position
- Fix hinges using ohmic heating, friction

Vibromotor results  
- Step size $0.27 \pm 0.16 \mu m$; near resonance, step size can change with small frequency variations
- Closed loop control necessary  

Daneman et al., BSAC

Using Beam Buckling

- Use in-plane forces to buckle clamped-clamped support beam out of plane
  - Can generate few $\mu N$, displace few tens of $\mu m$

Challenges
- Real estate requirements
- Need closed-loop control  

Garcia et al., Sandia Labs
Parallel External Methods

- Fluidic agitation
- Ultrasonic forces
- Magnetic deflection
- Polymer shrinkage
- Surface tension of droplets

Yi and Liu, U of Illinois

Parallel External Methods

- Polymer shrinkage
- Surface tension of droplets

E. Smela group Univ. of MD
Pop-Up MEMS

- Complex structures; one simple assembly step
- Sandia SUMMiT 4-level process used to fabricate pop-up MEMS

Closed Box Assembly
Lecture Outline

- Assembly of Hinged MEMS Structures
- Assembly of MEMS With Other Microdevices
- Serial Assembly (pick & place)
- Parallel Assembly Processes
  - Guided Transfer
  - Self-Assembly

Integration with Circuitry

- MEMS/CMOS co-fabrication
  - MEMS/CMOS mixed
    - “Boutique processes” (Analog Devices)
  - MEMS first, CMOS last
    - Need to own or control CMOS fab (Sandia)
  - CMOS first, MEMS last
    - Can use CMOS foundry; thermal budget for MEMS is a challenge

- Challenges
  - CMOS and MEMS wafer sizes
  - Material and process incompatibilities
  - Yield losses from high mask counts
  - MEMS-specific dicing and packaging

- Microassemble finished components instead?
**Smart Dust Mote**

- Passive CCR comm.
  - MEMS/polysilicon

- Sensor
  - MEMS/MEMS surface, ...

- Laser diode
  - H:Y process

- Active beam steering laser comm.
  - MEMS/optical quality polysilicon

- Analog I/O, DSP, Control
  - GPTS CMOS

- Power capacitor
  - Multi-layer ceramic

- Solar cell
  - CMOS or III-V

- Thick film battery
  - Solgel V2O5

1-2 mm

---

**Motivation for Integration**

- Advantages
  - increased functionality
  - higher performance
  - lower cost

- Next generation of microsystems
  - MEMS, microelectronic, microoptical, microfluidic components on a single substrate

---

Brittle star on SEM of brittle star "eyes"

**Joanna Aizenberg et al. Nature 2002**
**Why Microassembly?**

- Assembly vs. co-fabrication
  - Avoid materials and process incompatibilities and optimize elements separately
  - Reduce materials cost
  - Reduce yield losses

- Technique requirements
  - Massively parallel (low cost, high speed)
  - Microscale positioning precision
  - Mechanical bonding and electrical interconnection available

Adapted from K. Böhringer, et al, May 1998

---

**Assembly Classification**

- Lecture Outline
  - Assembly of Hinged MEMS Structures
  - Assembly of MEMS With Other Microdevices
  - Serial Assembly (pick & place)
  - Parallel Assembly Processes
    - Guided Transfer
    - Self-Assembly

- Serial microassembly ~ “pick and place” on the microscale
- Parallel microassembly ~ multiple parts assembled simultaneously
  - Guided: Pre-determined destination for parts ensured by guiding
  - Self-Assembling: Parts initially in random positions; energy minimization determines part destinations without active intervention
Robotic Microassembly

- Serial robotic “pick & place” assembly
  - Hierarchy of adhesive forces must be established

Microassembly System

- Commercial tooling advancing for high-density consumer electronics (e.g., cell phones ...5 x 10⁶ chip capacitors in a coffee mug (Murata, 2002)
- Suss MicroTEC bonder can achieve submicron accuracy in x, y, z
  - Imaging ~ optical mixing of two images
  - Robotic bonding arm ~ parts as small as 250×300 μm², range of bonding forces available (10 g to 200 kg), 6 DOF motion, temp. up to 450°C.
SUSS Microassembly

- Challenges
  - High cost, low speed
  - Surface effects do lead to unwanted adhesion
  - Compromised electrical performance

MEMS Actuator Arrays

- Use MEMS cooperatively
  - Regular grid of motion pixels move parts in parallel until they reach potential energy minima

- Microcilia arrays built on top of CMOS, Bohringer et al., 2000
  - Each actuator curls into/out of substrate plane due to CTE differences of 2 polyimide layers
  - Linear translation, diagonal motion, and vector field operations like centering and squeeze field manipulations possible
**Wafer-to-Wafer Transfer**

- Parallel assembly
  - Wafer-to-wafer transfer
  - Self-assembly

- Wafer-to-wafer transfer
  - Microstructures held on donor wafer by break-away tethers
  - Transferred occurs between aligned donor and target wafers

- Pros and Cons
  + Parallel assembly
  + Smaller area electrical connections
  - Inefficient use of materials
  - Yield losses

---

**Transfer Results**

- Transfer of Hexsil actuator onto CMOS wafer
Quality Factor Degradation

- Tuning fork resonator transferred
- Quality factor degradation observed
  - $3000 \pm 1500$ before transfer
  - $1200 \pm 500$ after (In metal)

Angad Singh, et al., Transducers ‘99

Recent Results

- Work by C. Nguyen group, U. of Michigan, Transducers ‘01
Self-Assembly

- Complex structures form using information embedded in components without individual guiding from outside influence
  - Binding sites are fabricated on the parts and substrates
  - Parts are initially randomly oriented.
  - When parts contact substrate, assembly occurs spontaneously due to energy minimization
  - Need background energy to move parts and remove incorrectly assembled parts

- Results from Alien Technology
  - 11,000 elements per minute
  - 99.99% yield
  - ±1 μm alignment

Alien Technology’s Fluidic Self-Assembly

CMOS Wafers → Micromachine Blocks
Glass Panel or Plastic Panel → Generate Holes
FSA
Complete Display (standard)
Alien Technology’s NanoBlocks™

Interconnected NanoBlocks™
Web Process for Continuous Fluidic Self-Assembly

Scaling of Forces

\[ F = \begin{cases} 
  s^4 & \text{magnetic} \\
  s^3 & \text{gravitational} \\
  s^2 & \text{electrostatic, surface, fluidic drag} \\
  s^1 & \text{capillary} 
\end{cases} \]

- Forces which scale with lower powers of length \( s \) become important at the microscale

W.S.N. Trimmer, Sensors & Actuators, 1989

Karen L. Scott, Ph. D., Howe and Radke groups, 2003
Other Self-Assembly Techniques

Polymer bridging
Nakakubo et al., 1999

Magnetic forces
Murakami et al., 1999

Gravity, capillary forces
Michael et al., 1998

Coulombic forces
Esener et al., 1998

Hierarchical Self-Assembly in Nature
Self-Assembly with Capillary Forces

- Separate surfaces into hydrophobic, hydrophilic regions
  - Matching hydrophobic binding sites
  - Hydrophilic remaining areas
  - Coat substrate sites selectively with hydrophobic liquid

+ No shape constraints on parts
+ No bulk micromachining of substrate
- Unique orientation possible?
- Electrical connections?

Surface Treatment

- Oxidize silicon, glass surfaces → hydrophilic
- Self-assemble monolayer on gold → hydrophobic
Microparts

Substrate Adhesive Coating

- Patterned substrate is passed through hydrocarbon adhesive-water interface

H. Biebuyck et al., Langmuir, 1994
Video Clip

Frames of Self-Assembly

- Video analysis
  - max $a = 0.76 \text{ m/s}^2$

- Once assembled
  - $F_{\text{capillary}, z} \sim 100\text{'}s \mu\text{N}$
  - $F_{\text{gravity}} = 26 \text{ nN}$
  - $F_{\text{drag}} \sim 10\text{'}s \text{ nN}$
Model of Capillary Forces

\[ y = -136.61x + 0.0798 \]

\[ R^2 = 0.99 \]

Surface Evolver software available at www.susqu.edu/facstaff/b/brakke.evolver.html

Alignment Precision

- Vernier scales with 0.2 \( \mu \text{m} \) resolution

- As-assembled in water, precision \( \leq 0.2 \mu \text{m} \)

- After curing, rotational precision \( \theta \leq 0.31^\circ \)
Mirrors onto Microactuators

- Adaptive optics application
- Assemble flat, high-quality mirrors onto MEMS actuators
- Si (100) mirrors
- MEMS actuators
  - nickel-polySi bimorph flexures
  - electrostatic actuation

U. Srinivasan, M.A. Helmbrecht, C. Rembe, R.S. Muller and R.T. Howe, BSAC
Assembly Results

- Procedure
  - Self-assembly
  - Adhesive activation
  - Sacrificial layer etch
  - Carbon dioxide supercritical point drying

- Stroboscopic interferometry
  - Mirror curvature less than 20 nm
  - Radius of curvature, 1.24 m

Self-Assembly with Interconnect

Inductor chiplets with electrical interconnects
Di Water
Hexadecane
Solder coated electrical interconnects

DI water
Low-T alloy
Microcomponent
Substrate
Hexadecane
Self-Assembly for Nanofabrication

Nanofabrication: Comparing the Methods

Researchers are developing an array of techniques for building structures smaller than 100 nanometers. Here is a summary of the advantages and disadvantages of four methods.

**Photolithography**
- **Advantages:** The electronics industry is already familiar with this technology because it is currently used to fabricate microchips. Manufacturers can modify the technique to produce nanometer-scale structures by employing electron beams, x-rays or extreme ultraviolet light.
- **Disadvantages:** The necessary modifications will be expensive and technically difficult. Using electron beams to fashion structures is costly and slow. X-rays and extreme ultraviolet light can damage the equipment used in the process.

**Soft Lithography**
- **Advantages:** This method allows researchers to inexpensively reproduce patterns created by electron-beam lithography or other related techniques. Soft lithography requires no special equipment and can be carried out by hand in an ordinary laboratory.
- **Disadvantages:** The technique is not ideal for manufacturing the multilayered structures of electronic devices. Researchers are trying to overcome this drawback, but it remains to be seen whether these efforts will be successful.

**Scanning Probe Methods**
- **Advantages:** The scanning tunneling microscope and the atomic force microscope can be used to move individual nanoparticles and arrange them in patterns. The instruments can build rings and wires that are only one atom wide.
- **Disadvantages:** The methods are too slow for mass production. Applications of the microscopes will probably be limited to the fabrication of specialized devices.

**Bottom-Up Methods**
- **Advantages:** By setting up carefully controlled chemical reactions, researchers can cheaply and easily assemble atoms and molecules into the smallest nanostructures, with dimensions between two and 10 nanometers.
- **Disadvantages:** Because these methods cannot produce designed, interconnected patterns, they are not well suited for building electronic devices such as microchips.